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Top Physics at Threshold and Beyond

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Abstract

A review on theoretical aspects of top quark physics at the Linear Collider is given with focus on the process $e^+e^- \to t\bar{t}$ and the presentations given at this conference.

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1 Introduction

Top quark physics constitutes one of the main tasks at the Linear Collider (LC). Top physics at the LC is in many respects complementary to top physics at the LHC. Although the LC has smaller statistics, it provides a much cleaner environment, which leads to smaller systematic uncertainties. One obvious reason is the fact that the top pair is produced in a colour singlet state rather than in an octet like at the LHC. Thus top physics at the LC can be expected to lead to results at a high level of precision. The basic property which makes precision studies of the top quark *per se* at all possible is its large mass: in the Standard Model (SM) the top decay width is dominated by the decay into a b quark and a W boson and reads $\Gamma_t = (G_F/\sqrt{2})(M_t^3/8\pi) \approx 1.5\,\text{GeV}$ at the Born level and in the limit of vanishing W mass. Because the width is much larger than the typical hadronisation scale, the top quark decays before hadronisation effects set in. This fact makes top meson spectroscopy impossible, but, at the same time, leads to a suppression of nonperturbative effects in top production and decay in any kinematic regime [1,2]. In many (but not all) respects, the top quark can be considered as a real particle, and properties like its polarisation are measurable observables, which can be determined from distributions of the top decay products. In addition, this feature allows the theorists to use perturbative methods to describe the top quark a high degree of precision [1,2].

In this talk I review some theoretical aspects of top quark physics at the LC focusing on the process $e^+e^- \to t\bar{t}$ and the presentations given at this conference. The presentation is subjective and not all issues of interest can be mentioned. However, I hope that this talk can reflect some of the flavour of the rich and interesting top phenomenology at the LC.

2 Threshold and Continuum

Because the c.m. energy of the e^+e^- collision is well known at the GeV level it is possible to resolve the $t\bar{t}$ threshold regime where Coulomb-like binding affects the $t\bar{t}$ dynamics. This allows to do top physics in two completely different theoretical settings. In the continuum far above the $t\bar{t}$ threshold ($\sqrt{s} \gtrsim 2M_t + 15\,\text{GeV}$) conventional perturbative methods can be employed, whereas close to threshold ($\sqrt{s} \approx 2M_t$) resummations of terms $\propto \alpha_s/v$, v being the c.m. top velocity, have to be carried out to all orders in α_s. Practically all top quark properties can be measured in the continuum as well as in the threshold regime. The different interplay

of the top quark properties with QCD in the two regimes allows for complementary tests of the SM and, in particular, of the strong interaction.

3 Top Mass

The top mass affects the relation between the electroweak precision observables indirectly through loop effects. In the parameter Δr, which relates M_W, M_Z, α_{em} and G_F, the top mass enters quadratically. The expected reductions of the uncertainties of quantities like the W mass and the weak mixing angle ($\delta M_W = 15(8)\,\text{MeV}$, $\delta \sin^2\theta_W = 18(1)\times 10^{-5}$ at LHC/LC (Giga Z))[3] make it desirable to determine the top mass as accurate as possible in order to improve the sensitivity to the Higgs mass or non-SM loop effects which enter Δr less strongly than the top mass[4]. Stringent bounds on the Higgs mass will provide a test of the SM Higgs mechanism. At the LC the top mass can be measured at the per mille level in two ways. The standard method is to reconstruct the top invariant mass distribution. Because systematic experimental effects (i.e. jet energy resolution, beam effects, gluon radiation) are quite well understood in the e^+e^- environment it will be possible to determine the peak of the distribution to a few hundred MeV[5] (compared to about 2 GeV at the LHC). Studies using dilepton events[6] have shown that the peak can be determined to 200 MeV. However, one has to keep in mind that, at present, it is not known how to relate the peak of the reconstructed invariant mass distribution to a theoretically clean quark mass definition. Intuitively the peak is most closely related to the pole mass, but the latter has an intrinsic theoretical ambiguity of order $\Lambda_{QCD} \approx 200$-$300$ MeV, also known as the "pole mass renormalon" problem. Related but not equivalent to this problem are QCD interconnection effects which arise from the colour rearrangement among the top and antitop decay products in the hadroformation process. The modelling of this phenomenon could lead to uncertainties in the peak of around 100 MeV[7]. In summary one can say that the peak in the invariant mass distribution is ambiguous to an amount of order Λ_{QCD} because a) the invariant mass (or the momentum) of a coloured particle is ambiguous, i.e. its exact meaning depends on the reconstruction method, and b) because some aspects of the colour rearrangement in the hadroformation process are not understood yet. More theoretical studies of this interesting subject have to be carried out to fully exploit the potential of the mass reconstruction method at the LC.

The second possibility to determine the top mass comes from a scan of the total $t\bar{t}$ cross section line-shape around the $t\bar{t}$ threshold. The rise and the shape of the cross section can be directly related to the top quark mass. The advantage of the threshold scan is that the total cross section describes the production rate of colour-singlet $t\bar{t}$ pairs. Thus the conceptual limitations and problems related to the top as a coloured particle and to the colour flow among the top decay products only play a minor (but not negligible) role. Just recently next-to-next-to-leading order (NNLO) QCD calculations for the total cross section have been carried out using the concept of effective field theories[8,9,10,11,12]. In this approach the hierarchy $M_t \gg M_t v\,(t \text{ momentum}) \gg M_t v^2\,(t \text{ kinetic energy}) > \Gamma_t \gg \Lambda_{QCD}$ is used to integrate out the dynamical degrees of freedom associated with the scales M_t and $M_t v$, and to derive field equations describing the $t\bar{t}$ dynamics. The NNLO

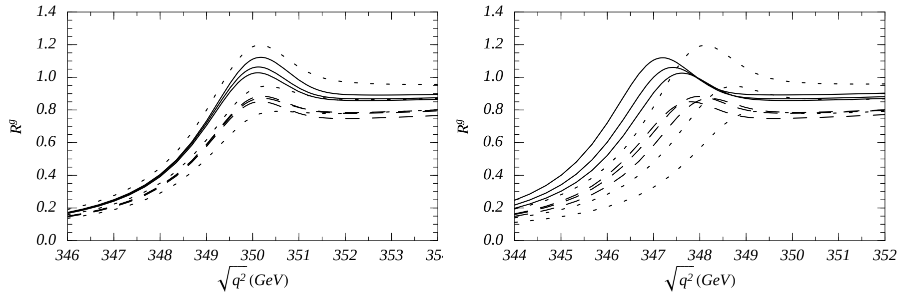

Figure 1: The total photon-induced $t\bar{t}$ cross section devided by the point cross section at the LC versus the c.m. energy in the threshold regime at LO (dotted curves), NLO (dashed) and NNLO (solid) in the $1S$ (left figure) and the pole (right figure) mass schemes for $\alpha_s(M_Z) = 0.118$ and $\mu = 15, 30, 60$ GeV. The plots have been taken from Ref.[11].

calculations demonstrate the inadequacy of the pole mass definition as it leads to NNLO corrections in the peak position which are as large at the NLO ones (see the right picture in Fig. 1 and also Ref. [13]). Several alternative mass definitions have been proposed which (on the conceptual side) avoid the Λ_{QCD}-ambiguity of the pole mass and (on the practical side) lead to a reduced correlation of the threshold line-shape to the choice of theoretical parameters like the renormalisation scale or α_s. In the left picture in Fig. 1 the total cross section is displayed using the so called $1S$ top mass definition [12,8]. (Similar results have been obtained with the so called PS mass [11].) The advantage of these alternative mass definitions is twofold: they allow for smaller theoretical uncertainties in the mass determination, and they can be related to the $\overline{\rm MS}$ mass, the preferred mass definition in the high energy continuum, more reliably than the pole mass. Simulation studies [14] have shown that the $1S$ and PS masses can be determined with theoretical and experimental uncertainties of around 100 MeV despite the beamstrahlung effects, which lead to an additional smearing of the cross section, and the remaining theoretical uncertainties in the normalisation of the total cross section.

A measurement of the $\overline{\rm MS}$ top mass at the level of 5 GeV can be achieved if the ratio of $t\bar{t}g$ events versus all $t\bar{t}$ events could be measured to 1% at at c.m. energy of 1 TeV [15]. This is possible because the $t\bar{t}g$ cross section also depends on the jet-resolution scale. For small jet-resolution scales the dependence on the top mass is enhanced. Calculations of the $t\bar{t}g$ versus $t\bar{t}$ ratio have been carried out at order α_s^2 and have shown that the order α_s^2 corrections are of order 30% [15]. Thus the calculation of higher order calculations is required. A determination of the top mass from the $t\bar{t}g$ versus $t\bar{t}$ ratio would not be able to compete in precision with the mass determination from the invariant mass distribution or the threshold scan, but it would serve as a cross check for the previously mentioned methods.

4 Strong Coupling

The strong coupling governs the Coulombic attraction of the $t\bar{t}$ pair in the threshold regime. The resummations of terms $\propto \alpha_s/v$ to all orders lead to a strong dependence

of the normalisation of the threshold cross section on α_s, $\sigma_{t\bar{t}} \sim |\Psi_{t\bar{t}}(0)|^2 \sim \alpha_s^3$. Thus one might conclude that the threshold scan would be a reliable way to determine the strong coupling. The newly available NNLO corrections for the threshold cross section, however, also reveal that the uncertainty in the normalisation of the cross section is still significant, at least at the order 10%[8,9,10,11,12] (see Fig 1). Taking the size of the NNLO normalisation corrections as an uncertainty leads to an uncertainty in $\alpha_s(M_Z)$ of 0.012, which is five times larger than the combined systematic and statistical experimental error[14]. (The present normalisation uncertainty of the cross section at threshold also makes a measurement of the Higgs mass or the top Yukawa coupling from the cross section impossible. The Higgs mass affects the cross section through electroweak corrections to the $t\bar{t}$ production vertex and through a Yukawa interaction potential. For M_h around 100 GeV the effects of the Yukawa potential are negligible and the Higgs effects in the vertex corrections are at the level of several percent and quickly decrease if M_h is larger[16].) This shows that a better understanding of the normalisation of the threshold cross section is mandatory, which can probably only be achieved by a calculation of all N^{3}LO corrections. In principle, α_s can also be determined from more differential threshold quantities like the top three-momentum distribution or the angular distribution. The NNLO corrections for those quantities are not completed yet, and are expected to be sizeable. Of particular interest in this respect is the problem of nonfactorizable corrections, which come from the exchange of gluons among the top and the top decay products. This problem is closely related to the colour reconnection problem mentioned before.

A study has also been carried out on the α_s-determination from the ratio $\sigma_{t\bar{t}}/\sigma_{\mu^+\mu^-}$ above threshold[17]. For c.m. energies above 0.5 TeV theoretical uncertainties are below 0.5%. The uncertainty in a determination of $\alpha_s(M_Z)$ is then dominated by the luminosity measurement. Assuming an uncertainty of about 2% for the luminosity leads to an error in $\alpha_s(M_Z)$ of about 0.007. This could serve as a cross check for other α_s-determinations[18].

The ratio of $t\bar{t}g$ events versus all $t\bar{t}$ events might also be used as a means to determine α_s. The uncertainties of the order α_s^2 calculations known at present[15] do, however, not allow to draw any definite conclusions.

5 Top Yukawa Coupling

By the time when the LC starts operation the LHC will probably have already discovered the Higgs boson and determined its mass. A direct measurement of the top Yukawa coupling g_{tth} will then provide an important test whether the SM Higgs mechanism, which leads to $g_{tth}^2 = \sqrt{2} G_F M_t^2$, is indeed realized for the quark mass generation. Deviations from the SM value might indicate a different mass generation mechanism, or could be a reflection of an extended Higgs sector, which would make the Yukawa couplings also depend on the Higgs mixing angles. For a light Higgs ($M_h < 2M_t$), the situation which is favoured by supersymmetric models and which has been mainly studies up to now, the reaction $e^+e^- \to t\bar{t}h$ is best suited for a direct measurement of g_{tth}. The experimental signature $WWbbbb$ with 6 or 8 jets is spectacular. Complete order α_s calculations exist in the SM and the

minimal supersymmetric SM (MSSM) [19]. The order α_s^2 corrections are expected to be small. In general, the cross section is below a few fb, which makes collider designs with high luminosity desirable. Simulations have shown [20] that for the 6 and the 8 jet mode relative (combined statistical and systematical) uncertainties in g_{tth} below 10% can be achieved for a Higgs mass around 120 GeV at $\sqrt{s}$ =800 GeV and an integrated luminosity of 1000 fb^{-1}. Corresponding LHC studies yield larger uncertainties. For a heavy Higgs ($M_h > 2M_t$) the modes $e^+e^- \to Zh(\to Zt\bar{t})$ and $e^+e^- \to \nu\bar{\nu}h(\to \nu\bar{\nu}t\bar{t})$ are dominant.

6 Anomalous Couplings, CP violation, Correlations

The clean LC environment allows for many different ways to test the charged or neutral current top quark couplings for non-SM or CP-violating contributions. The possibility to change the electron-positron beam polarisations can enhance the sensitivity of observables to those effects. Studies have been carried out for CP-even observables like lepton energy spectra[21] or the gluon energy spectrum in $e^+e^- \to t\bar{t}g$[22], CP-odd asymmetries and CP-odd spin-momentum correlations of the top decay products. Measurements are possible at threshold and in the continuum, although statistics at threshold will be somewhat worse because only a relative small amount of luminosity will be spent there. In general, sensitivities at the level of a several to ten percent could be achieved, but a high luminosity is needed to reach interesting sensitivities for many models.

Although CP-violation is implemented into the SM through phases in the CKM matrix elements, it is practically impossible to detect SM CP-violation in top physics. This is a consequence of the GIM mechanism, which is particularly effective owing to the large top quark mass. (For exactly the same reason is B physics very much suitable to measure the CKM phase.) Observed CP-violating effects in observables related to the top quark would be a clear signal of new physics. On the other hand, the CKM phase is unlikely to be the only source of CP-violation in baryogenesis. Of particular interest is CP-violation which originates from the Higgs sector [23]. It would have good chances to be detected in top physics because the top Yukawa couplings are enhanced by the large top quark mass. In multi-Higgs-doublet models (MHDM's) CP-violation can be either implemented explicitly or, in models with more than two Higgs doublets, arises spontaneously. In MHDM's the top Yukawa couplings could also be further enhanced due to their dependence on the Higgs mixing angles. In 3HDM's CP-odd τ transverse polarisation asymmetries in the Higgs decay $t \to b\tau\nu$ could reach order 10%. An observation would signal CP-violation in the charged Higgs sector. In certain 2HDM's CP-violating phases in the neutral sector could be detected for small values of $\tan\beta$(=ratio of the two VEV's) in the processes $e^+e^- \to t\bar{t}h$ and $e^+e^- \to t\bar{t}Z$ using momentum correlations and optimised observables[23]. For $M_h > 2M_t$ and known Higgs mass it might also be possible to reconstruct the decay $h \to t\bar{t}$ from $e^+e^- \to t\bar{t}Z$[24] or from $e^+e^- \to t\bar{t}\nu_e\bar{\nu}_e$[25]. For sufficiently high luminosity CP-violating phases could then be measured in spin-momentum correlations.

7 Top Decay

Apart from the standard final state reconstruction method, a promising way for a direct determination of the top quark width could be the threshold scan or the measurement of the forward-backward asymmetry in top quark production close to threshold. The peak of the total cross section is more pronounced for smaller top width, whereas the width dependence of the forward-backward asymmetry originates from the overlap of $t\bar{t}$ S-wave and P-wave amplitudes which is bigger for larger top width. At present, however, no definite conclusions can be drawn in view of the (potentially) large NNLO corrections. In addition, the problems of unambiguously defining the direction of flight of the top as a coloured particle and of properly understanding the effects of nonfactorizable corrections need to be addressed. Putting the problems of uncalculated higher order corrections and the conceptual issues just mentioned aside, experimental uncertainties of 10-20% could be achieved from the threshold [26]. A method to extract the top width from the interference of decay and production stage radiation of gluons in the process $e^+e^- \to t\bar{t}g$ has been investigated [27]. However, no definite conclusions can yet be drawn here either.

Due to the strong CKM and GIM suppressions any observed top decay other than into a bottom quark and a W boson would practically imply non-SM physics. In is therefore interesting to examine non-SM decay modes of the top quark. For the LC we have to keep in mind that branching ratios for rare decays must be larger than order 10^{-5} to be visible. The work on this rich subject has been extensive for the LC and also for the LHC and only a few impressions can be given here. In supersymmetric extensions of the SM top decays into charged Higgs bosons ($t \to bH^+$) and into stops and neutralinos ($t \to \tilde{t}\tilde{\chi}^0_1$) or sbottoms and charginos ($t \to \tilde{b}\tilde{\chi}^+_1$) are possible. If kinematically allowed, those modes can have branching ratios of more than 10% using the present constraints on supersymmetric parameters. The observation of $t \to bH^+$ would not necessarily be a hint for supersymmetry because this mode also exists in general multi-Higgs models. In the framework of the MSSM the FCNC decay $t \to Xc$ is dominated by final states containing neutral Higgs bosons and could reach a branching ratio [28] of several 10^{-4}.

8 Summary

The prospects for the top mass determination at the level of 100-200 MeV at the LC are very good. The mass determination from the threshold scan of the total $t\bar{t}$ cross section line-shape seems well understood. Some more conceptual progress has to be achieved to control the mass reconstruction method at the same level. At present it seems difficult to achieve measurements of α_s from top observables which could compete with other methods, and probably the best way to proceed is to take α_s as an input from somewhere else. A better understanding of the normalisation of the $t\bar{t}$ threshold cross section is needed improve this situation. The determination of the top Yukawa coupling is well studied for the case of a light Higgs for the reference process $e^+e^- \to t\bar{t}h$; uncertainties below 10% seem realistic from 6 and 8 jet modes. CP-violating phases from models with extended Higgs sectors can be accessible for sufficient luminosity. The physics of non-standard top decays is

very rich. A number of rare decay modes that could be visible at the LC exist in extensions of the SM.

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